





Parametric study for a rapid cycling synchrotron

by Antoine Chance (CEA Paris-Saclay) Acknowledgements: F. Batsch, H. Damerau, I. Karpov David Amorim, Scott Berg, Fulvio Boattini, Luca Bottura, Christian Carli, Alexej Grudiev, Elias Metral, Daniel Schulte



- Hybrid RCSs have intersecting normal conducting (NC) and superconducting (SC) magnets
- The studies presented aim to determine the RF (cavity) and lattice parameter (number of RF stations, momentum compaction factor,...)



A lot of constraints



- Muons decay very fast (Rest lifetime: 2.2 µs):
- We should accelerate as fast: τ_{acc} as low as possible.
 - Muon survival: $\frac{N_{ext}}{N_{inj}} = \left(\frac{E_{ext}}{E_{inj}}\right)^{-\frac{\tau_{acc}}{\tau_{\mu}(\gamma_{ext}-\gamma_{inj})}}$ for a linear ramp
- To decrease cost operation, we should:
 - Minimize the total voltage and thus energy gain per turn: Energy gain: $\Delta E = \frac{E_{ext} - E_{inj}}{\tau_{acc}} \frac{L_{RCS}}{c} \Rightarrow$ RCS as small as possible
 - Interest of a hybrid RCS: higher average field \Rightarrow smaller synchotron.
 - But different path lengths and orbits.
 - Optimize the dipole ramp to minimize the power consumption (see Fulvio's talk).
- Find the best ratio extraction/injection ratio between the different acceleration stages.

A. Chance, Muon Collider collaboration meeting, 11-14 October 2022



$$L_{NC} = 2\pi \frac{B\rho_{ext} - B\rho_{inj}}{B_{NC,ext} - B_{NC,inj}} = \pi \frac{B\rho_{ext} - B\rho_{inj}}{B_{NC}}$$
$$L_{SC} = 2\pi \frac{B\rho_{inj}B_{NC,ext} - B\rho_{ext}B_{NC,inj}}{B_{SC}(B_{NC,ext} - B_{NC,inj})} = \pi \frac{B\rho_{inj} + B\rho_{ext}}{B_{SC}}$$



Development of a python package to integrate the different constraints Any help is welcome !



Parameters and tools: General parameter



Courtesy: Fabian Batsch

Detailed parameter table: <u>https://cernbox.cern.ch/index.php/s/I9VpITncUeCBtiz</u>

	RCS1 → 314 GeV	RCS2 → 750 GeV	RCS3 → 1.5 TeV
Circumference, $2\pi R$ [m]	5990	5590	10700
Energy factor, $E_{\rm ej}/E_{\rm inj}$	5.0	2.4	2.0
Repetition rate, f_{rep} [Hz]	5 (asym.)	5 (asym.)	5 (asym.)
Number of bunches	1μ⁺, 1μ⁻	1μ+, 1μ ⁻	1μ⁺, 1μ⁻
Bunch population	2.5*10 ¹²	2.3*10 ¹²	2.2*10 ¹²
Survival rate per ring	90%	90%	90%
Acceleration time [ms]	0.34	1.04	2.37
Number of turns	17	55	66
Energy gain per turn, ΔE [GeV]	14.8	7.9	11.4
Acc. gradient for survival [MV/m]	2.4	1.3	1.1
Acc. field in RF cavity [MV/m]	30	30	30
Max. RF voltage for ϕ_s =135° [GV]	20.9	11.2	16.1

Basic data Basic data Particles Costs Costs Type Dynamics Acceleration time Injection energy Ejection energy Ejection energy Ejection energy Momentum at e Number of turns Planned Survival rate Accel, cracitan, linear for survival Required energy gain per turn Transition gamma Injection relativistic mass factor Ejection relativistic mass factor Injection vic Ejection	Symbol - </th <th>Unit MC </th> <th>Value μ RCS 0.34 63000 313830 4.98 63106 313935 17 0.9 0.9 2.44 14755 20.41 597 2971</th> <th>Details</th> <th>Value μ hybrid RCS 1.09704595 313830 750000 2.39 313935 750106 55 0.9 0.81 1.33 7930 20.41</th> <th>Details</th> <th>Value μ hybrid RCS 2.37 750000 1500000 2.00 750106 1500106 66 0.9 0.729 1.266 11364 ~30</th>	Unit MC 	Value μ RCS 0.34 63000 313830 4.98 63106 313935 17 0.9 0.9 2.44 14755 20.41 597 2971	Details	Value μ hybrid RCS 1.09704595 313830 750000 2.39 313935 750106 55 0.9 0.81 1.33 7930 20.41	Details	Value μ hybrid RCS 2.37 750000 1500000 2.00 750106 1500106 66 0.9 0.729 1.266 11364 ~30
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Accel, cradient, linear for survival Required energy gain per turn Transition gamma Injection relativistic mass factor Ejection vic Ejection vic Ejection vic	G ΔE γ_{ty} γ_{tij} β_{tij} β_{tij}	[MV/m] [MeV] - - - - 96	2.44 14755 20.41 597 2971		1.33 7930 20.41		1.06 11364 ~30
Required energy gain per turn Transition gamma Injection relativistic mass factor Ejection relativistic mass factor Injection vic Ejection vic Parameter Classical RCS	ΔE Y_{tr} Y_{tei} R_{tei} R_{tei}	[MeV] - - - %	14755 20.41 597 2971		7930 20.41		~30
Transition gamma Injection relativistic mass factor Ejection relativistic mass factor Injection vic Ejection vic Parameter Classical RCS	$rac{Y_{tr}}{Y_{tri}}$ $rac{Y_{tri}}{r_{ti}}$ eta_{tri} eta_{tri}		20.41 597 2971		20.41		~30
Transition gamma Injection relativistic mass factor Ejection relativistic mass factor Injection v/c Parameter Classical RCS	$\begin{array}{c} Y_{tr} \\ Y_{tri} \\ Y_{tri} \\ \beta_{tri} \\ \beta_{tri} \\ \beta_{tri} \end{array}$	- - - %	20.41 597 2971		20.41		~30
Injection relativistic mass factor Ejection relativistic mass factor Injection v/c Ejection v/c Parameter Classical RCS	γ_{tel} γ_{tel} β_{tel} β_{tel}	96	597				
Ejection relativistic mass factor Injection v/c Ejection v/c Parameter Classical RCS	Υ _{ni} β _{ni} β _{ni}	- %	2971		2071		7000
Ejecuon relativistic mass factor Injection v/c Ejection v/c Parameter Classical RCS	τ _{ei} β _{ei} β _{ei}	%	2971		20/1		7099
Injection v/c Ejection v/c Parameter Classical RCS	ρ _{ini} β _{si}	%	2011		7099		14198
Ejection v/c Parameter Classical RCS	β _{gi}		0.9999986		0.999999943		0.9999999901
Parameter Classical RCS		%	0.999999943		0.9999999901		0.9999999975
Parameter Classical RCS							
Radius	R	[m]	953.3		953.3		1703.0
Circumference	2πR	[m]	5990		5990		10700
Circumference Ratio	B ₁₊₁ /B ₁	-	-		1		1.79
Pack fraction	?		0.61		0.61		0.628
Bend radius	P ₈	m	581.8		581.8		1070.2
Tot. straight section length	Law	[m]	2334.7		2335.7		3975.7
Injection bending field (average)	Bini	(T)	0.36		1.80		2.34
RF			I I			1	
Systems			TESLA		TESLA		TESLA
Main RE frequency	for	[MHz]	1300		1300		1300
Harmonic number	h	-	25957		25957		46367
Revolution frequency ei	f	[kHz]	50.08		50.08		28.04
Revolution period	Trev	fusl	20.0		20.0		35.7
Max RE voltage	V.	[GV]	20.87		11.22		16.07
Max RF power	P	[MW]					
RF Filling factor			0.4		0.4		0.45
Number RF stations		-	Around 50		Around 50		Around 50
Cavities			9-cell		9-cell		9-cell
Number of cavities	?	-	696		374		536
Peak Impedance		[Ω]	-				
Gradient in cavity	$\Delta E/L$	[MV/m]	30		30		30
Average energy gain per total straight	$\Delta E/L$	[MeV/m]	6.3		3.4		2.9
Accelerating field per total straight	$\Delta E/L$	[MeV/m]	8.9		4.8		4.0
Accelerating field gradient, with FF	$\Delta E/L$	[MV/m]	22.3		12.0		9.0
Stable phase	\$ 5	[°]	45		45		45
Conversion factor mm mrad – eVs		Vs/mm mra	69.40		165.86		331.72
Longitudinal emittance (σE * 4σz)	۶ ¹ .,	[eVs]	0.025	7.5 MeV m	0.025		0.025
Longitudinal emittance (phase space area)	51	[eVs]	0.079		0.079		0.079
Injection bucket area	Anini	[eVs]	0.62		1.01		1.40
Ejection bucket area	Anti	[eVs]	1.37		1.56		1.97
Bucket area reduction factor	A _R IA _{R-1}		0,172		0.172		0,172
Horizontal betatron tune	0.						
Vertical betatron tune	0	-					
Average horizontal Twiss beta	ßh	[m]	10		10		10
Average vertical Twiss beta	βv	[m]	10		10		10
Injection synchrotron frequency	ferm	[kHz]	76 33		25.07		14 53
Election synchrotron frequency	5.03 f	[kHz]	34 20		16.22		10.37
Injection synchrotron tune O	£ . /f	[KH2]	34.20		16.22		10.27
Figetion synchrotren tune 0	Sing tax		1.52		0.50		0.52

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What is new since February



- The user chooses the synchrotron gemetry, injection and extraction phase (the dipoles are oscillating) and defines the dipole families and the dipole patterns.
- The code calculates:
 - The dipole period (compromise between the maximum voltage, the maximum field slope and the minimum acceleration time)
 - The energy and synchronous phase variation
 - The muon survival
 - The optimum dipole lengths for each dipole
 - The path length variation and the needed aperture
 - Some optics parameters (momentum compaction, beam size) by assuming FODO cells (that should be improved in the future).



Example of dipole ramp in the RCS ME



- Harmonic dipole: $1.8 \sin \phi 0.38197 \sin 2\phi$
- Muon survival: 89.60% (linear ramp) against 89.58% (harmonic dipole): negligible difference





 n_c

 n_d

 Δ_c

 L_1

 L_2

 L_{dd}





Total path length: analytic formulae



$$\mathcal{S}_T - \mathcal{S}_{T,a}^* = \frac{a(b-1)\pi^2}{3n_d(1+n_d)n_c} \left[L_T \frac{ab+n_d}{4n_c} + L_{dd} \left(n_d(n_d-1) + a(b+1)(1+2n_d) \right) \right] + o(\frac{1}{n_c^2})$$

The total path length difference scales as $\frac{1}{n_c^2}$ when the total dipole length is large compared to the total distance used for the dipole spacing. For very large n_c we are driven by the spacing between the dipoles. If $4n_cn_dL_{dd} \ll L_T$,

$$S_{T} - S_{T,a}^{*} \propto \frac{1}{n_{c}^{2}}$$
$$S_{T} - S_{T,a}^{*} \propto \frac{a b + n_{d}}{n_{d}(1 + n_{d})}$$

Clear interest to increase the number of cells and dipoles per halfcell.





RCS ME: NC dipoles first variation with the number of cells nc



Total path length difference [m] 10^{1} Dipole length [m] 10^{-1} 10^{0} NC 3 dipoles NC 5 dipoles 10^{-2} NC 7 dipoles 3 dipoles SC 3 dipoles -- SC 5 dipoles • 5 dipoles 7 dipoles --- SC 7 dipoles 10 10^{-1} 100 200 300 400 500 600 200 300 400 500 600 100 Total number of dipole sets Total number of dipole sets Minimum dipole full aperture [mm] 101 101 – 3 dipoles - 5 dipoles compaction 10⁻² 7 dipoles --- No shift 3 dipoles No shift 5 dipoles ––– No shift 7 dipoles Momentum 5 10-3 - 3 dipoles Hor. 5 dipoles Hor. 7 dipoles Hor. – No shift 3 dipoles – – No shift 5 dipoles 100 300 400 500 600 100 200 300 400 500 600 100 200 Total number of dipole sets Total number of dipole sets Muon Collider collaboration meeting, 11-14 October 2022 A. Chance,

We assume an interconnection length of 0.3 m and dipoles of 2 m.

We consider a beam stay clear of 6 sigmas and FODO cells with a phase advance of 90 degrees. The magnet screening is not included and should be added to get the inner dipole aperture.

The vertical lines corresponds to the limit value of nc where there ins no space anymore to locate the quadrupoles.

That is better to have 5 or 7 dipoles per cell.



RCS ME: NC dipoles first variation with the SC dipole field



10 3 dipoles Total path length difference [m] 5 dipoles 10¹ 7 dipoles 10⁰ Dipole length [m] 10⁰ NC 5 dipoles 10-2 NC 7 dipoles SC 3 dipoles SC 5 dipoles --- SC 7 dipoles 10^{-3} 10^{-1} 10.0 10.5 8.0 8.5 9.0 9.5 11.0 11.5 12.0 9.0 9.5 10.0 10.5 11.0 11.5 12.0 8.0 8.5 Superconducting dipole field [T] Superconducting dipole field [T] Minimum dipole full aperture [mm] 10_1 10_1 3 dipoles Hor. — 3 dipoles 5 dipoles Hor. — 5 dipoles 7 dipoles 7 dipoles Hor. --- No shift 3 dipoles --- No shift 3 dipoles 6×10^{-4} No shift 5 dipoles --- No shift 5 dipoles - No shift 7 dipoles 4×10^{-4} 3×10^{-4} 2×10^{-4} 10 8.5 9.0 9.5 10.0 10.5 11.5 12.0 10.0 10.5 11.0 11.5 12.0 8.0 11.0 8.5 9.5 8.0 9.0 Superconducting dipole field [T] Superconducting dipole field [T] Muon Collider collaboration meeting, 11-14 October 2022 A. Chance,

We assume an interconnection length of 0.3 m and dipoles of 2 m.

We consider a beam stay clear of 6 sigmas and FODO cells with a phase advance of 90 degrees.

The number of cells is calculated to maximize the filling ratio of the arcs.

We assume a total number of 16 RF sections (and thus arcs), which explains the steps (number of cells is a multiple of 16).





RCS ME: SC dipoles first variation with the number of cells nc



Total path length difference [m] 10¹ 10⁰ Dipole length [m] 10^{-1} 10^{0} NC 3 dipole NC 5 dipoles NC 7 dipoles 10^{-2} 3 dipoles SC 3 dipoles --- SC 5 dipoles 5 dipoles 7 dipoles --- SC 7 dipoles 10 10^{-1} 100 200 300 400 500 600 200 300 400 500 600 100 Total number of dipole sets Total number of dipole sets Minimum dipole full aperture [mm] 101 101 – 3 dipoles - 5 dipoles - 7 dipoles compaction --- No shift 3 dipoles – – No shift 5 dipoles 10^{-2} ––– No shift 7 dipoles AND THE OWNER OF THE OWNER Momentum 10-3 3 dipoles Hor. 5 dipoles Hor. 7 dipoles Hor. -- No shift 3 dipoles – – No shift 5 dipoles No shift 7 dipoles 100 300 400 500 600 100 300 400 500 600 100 200 200 Total number of dipole sets Total number of dipole sets Muon Collider collaboration meeting, 11-14 October 2022 A. Chance,

We assume an interconnection length of 0.3 m and dipoles of 2 m.

We consider a beam stay clear of 6 sigmas and FODO cells with a phase advance of 90 degrees. The magnet screening is not included and should be added to get the inner dipole aperture.

The vertical lines corresponds to the limit value of nc where there ins no space anymore to locate the quadrupoles.

SC dipoles first is better than NC dipoles. No gain to go to 7 dipoles.



RCS ME: SC dipoles first variation with the SC dipole field



0.0275 3 dipoles NC 3 dipoles 5 dipoles 0.0250 NC 5 dipoles 5 7 dipoles NC 7 dipoles 0.0225 SC 3 dipoles Dipole length [m] -- SC 5 dipoles 0.0200 - SC 7 dipoles 0.0175 0.0150 0.0125 2 2 **=** 0.0100 IULA 0.0075 9.5 10.0 10.5 11.0 11.5 12.0 8.0 8.5 9.0 8.5 9.5 10.0 10.5 11.08.0 9.0 11.512.0 Superconducting dipole field [T] Superconducting dipole field [T] Minimum dipole full aperture [mm] 3 2 2 0 25 20 12 3 dipoles Hor. — 3 dipoles 5 dipoles Hor. – 5 dipoles 7 dipoles Hor. 7 dipoles -- No shift 3 dipoles No shift 3 dipoles 6×10^{-4} -- No shift 5 dipoles --- No shift 5 dipoles -- No shift 7 dipoles – - No shift 7 dipoles 4×10^{-4} 3×10^{-4} 2×10^{-4} 8.5 9.0 9.5 10.0 10.5 12.0 10.0 10.5 11.0 11.5 12.0 8.0 11.0 11.5 8.5 9.5 8.0 9.0 Superconducting dipole field [T] Superconducting dipole field [T] A. Chance, Muon Collider collaboration meeting, 11-14 October 2022

We assume an interconnection length of 0.3 m and dipoles of 2 m.

We consider a beam stay clear of 6 sigmas and FODO cells with a phase advance of 90 degrees.

The number of cells is calculated to maximize the filling ratio of the arcs.

We assume a total number of 16 RF sections (and thus arcs), which explains the steps (number of cells is a multiple of 16).



RCS ME: Case SC first with 5 dipoles and nc=208



That is possible to get a path length variation of about 1 cm. However, the cell is very compact.

Although the energy ramp is quasi-linear, the synchronous phase varies by more than 10 degrees.

The voltage is assumed to be constant in the cavity.





Is 300 GeV optimum as an intermediate energy?





A. Chance, Muon Collider collaboration meeting, 11-14 October 2022

- We make vary the injection energy in RCS ME.
- We adjust the filling factor and number of cells to keep a cell length of about 30 m in the arcs.

dipole slope [kT/s]

Maximum

400

375

400

- We consider a maximum field slope of 5 kT/s.
- At lower energy, we are limited by the maximum dipole slope.
- At higher energy, we are limited by the maximum dipole field.
- An energy of 300 GeV is a good starting point.



Conclusions



- An analytical model has been developed to evaluate the path lenth variation and the trajectory difference. We have now scaling rules and the model has been extended to an arbitrary number of dipole families.
- A python script has been developed to use these formulae and generate different RCS geometries.
- Concerning the RCS ME, the best dipole patterns are with the SC dipole first and 5 dipoles. More dipoles does not help because of the needed space for the interconnections.



Next steps



- The same study can be extended for the RCS HE and the RCS to go to 5 TeV (the baseline is still preliminary).
- That would be useful to optimize the injection/extraction energy of each step.
- The optics is based on FODO cells but that may be not the good assumption. Indeed, the number of RF sections becomes very large (more than 32, see Fabian Batsch's presentation). The number of FODO cells between 2 RF sections may become very low (5-10). Other optics may be more appropriate: we need to integrate the RF section in the cell. The direct impact is a change of the momentum compaction and the beam sizes.
- We can also choose to have more than one dipole block per half-cell. That is also a direction to increase the filling factor of the arcs and thus to reduce the path length variation.
- Some limitations like the minimum dipole length or the maximum quadrupole gradient are missing. That would be very useful to get these data to add constraints on the parameter set.



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Thank you for attention